

Surface exchange between the Weddell and Scotia Seas

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[1] Within Drake Passage, the southern flank of the Antarctic Circumpolar Current (ACC) hosts the ventilation of deep water, the injection of Antarctic shelf waters and interactions between westward and eastward boundary currents. This exchange is explored through the trajectories of forty surface drifters released in January 2012 in the northwestern Weddell Sea. The drifters detail Lagrangian transport pathways between the eastern Antarctic Peninsula and sites of elevated chlorophyll in the Scotia Sea. ACC frontal currents, in particular the Southern ACC Front, act as dynamical transport barriers to the drifters and influence surface chlorophyll distributions, indicating that ACC fronts partition Weddell source waters in the Scotia Sea. Interannual fluctuations in surface chlorophyll in the south Scotia Sea and the northern Weddell Sea covary. This suggests that Scotia Sea ecosystem dynamics are linked to water properties injected from the tip of the Antarctic Peninsula and respond to Weddell Gyre circulation changes.

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1. Introduction

[2] The intermittent and spatially localized nature of exchange between the Antarctic margins and the Antarctic Circumpolar Current (ACC) results from topographic steering, surface wind forcing and interactions with the cryosphere. Adding to this complexity, sites of exchange for surface/intermediate and deep water masses rarely coincide [e.g., Whitworth *et al.*, 1994]. The Weddell Sea is the largest independent circulation feature south of the ACC and is responsible for substantial modification of water masses: Circumpolar Deep Water enters the eastern side of the gyre, while Antarctic Bottom Water, Modified Circumpolar Deep Water and surface waters exit along the gyre's northwestern boundary. As much as 12 Sv, largely confined to narrow boundary currents, exits the gyre through the Weddell-Scotia Confluence (WSC) [Palmer *et al.*, 2012] (Figure 1). In addition to the injection of temperature and salinity characteristics and recently ventilated gas properties into the ACC, these waters may also be a significant source of micronutrients, such as iron, that influence Southern Ocean biogeochemical cycles [Falkowski *et al.*, 1998; Ardelan *et al.*, 2010; Frants *et al.*, 2012].

[3] The intricate structure of the Weddell Sea frontal currents, most notably the Antarctic Slope Front (ASF), has been revealed in recent years through high resolution hydrographic sections [Palmer *et al.*, 2012], Lagrangian instruments [Thompson *et al.*, 2009] and ocean gliders. Heywood *et al.* [2004] provided the first map of fronts in this region, identifying the cyclonic circulation around Powell Basin that separates intermediate and deep water masses from bottom waters that exit the Weddell Sea east of the Orkney Plateau. Thompson *et al.* [2009] confirmed much of this original map with a fleet of surface drifters, which emphasized the importance of topographic steering and illustrated the complicated path of the ASF around Hesperides Trough. Palmer *et al.* [2012] collected hydrographic sections of the ASF around Hesperides Trough and showed that transport is localized in tight boundary currents, often no wider than 10 km. Direct observations of the fate of Weddell Sea waters upon reaching the ACC are limited. Renner *et al.* [2012] tracked virtual drifters in an eddy permitting ocean GCM to show that drifters tend to be advected toward South Georgia Island (SGI), a site of elevated chlorophyll in the Southern Ocean [Park *et al.*, 2010]. Kahru *et al.* [2007], focusing on a region upstream of the WSC, provide evidence that much of the exchange between the Antarctic Peninsula's continental shelf and the Scotia Sea occurs through the action of mesoscale eddies.

[4] Most of the Southern Ocean is classified as a high-nutrient, low-chlorophyll environment, limited by micronutrients, such as iron. Eastern Drake Passage and the Scotia Sea are regions of anomalously high chlorophyll concentrations. Hofmann *et al.* [1998], Thorpe *et al.* [2004], and Murphy *et al.* [2004], among others, propose that currents carrying nutrients or organisms off the continental shelf provide key environmental links between the northwestern Weddell Sea and the Scotia Sea. While the iron cycle is this region is complex, involving lateral transfer, particulate sinking and vertical mixing, multiple studies [Tagliabue *et al.*, 2009; Dulaiova *et al.*, 2009] have shown that productivity in the south Scotia Sea is dominated by the lateral flux of sedimentary sources of iron, as opposed to aeolian, iceberg, and sea ice sources. (M. R. Wadley *et al.*, The role of iron sources and transport for Southern Ocean productivity, *Deep Sea Research*, in revision, 2013), echoing results by Lancelot *et al.* [2009], quantify this contribution by showing that 75% of Scotia Sea productivity is driven by sedimentary iron, originating from the Weddell Sea and the WSC. These studies both show that the introduction of sedimentary iron sources results in chlorophyll peaks that extend well into the central Scotia Sea.

[5] Thompson *et al.* [2009] attempted to map the transport pathways between the Antarctic Peninsula and SGI using Lagrangian drifters, but sea ice encroachment resulted in only three drifters entering the ACC (Figure 1). The ACC itself is partitioned into a series of hydrographic fronts

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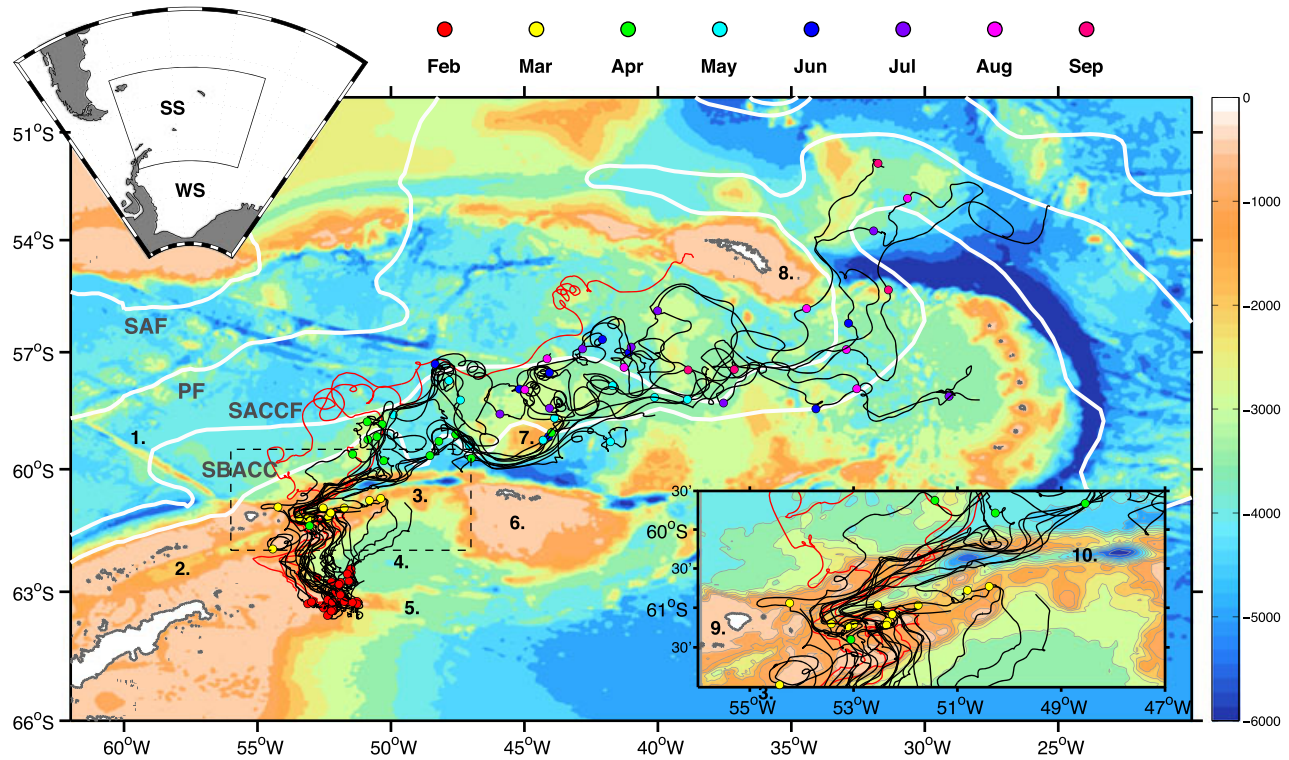


Figure 1. Map of the northwestern Weddell Sea (WS) and the Scotia Sea (SS), with colors indicating depth in meters. The black curves show trajectories of 40 surface drifters deployed at Joinville Ridge in late January 2012 and the colored circles indicate position on the first day of the month given in the key. Three red curves show trajectories of surface drifters from a previous deployment in 2007. White curves show the climatological positions of the ACC fronts (SAF, Subantarctic Front; PF, Polar Front; SACCF, Southern ACC Front; SBACC, Southern Boundary) from Orsi *et al.* [1995]. Geographic locations discussed in the text are numbered: 1. Shackleton Fracture Zone, 2. Bransfield Strait, 3. South Scotia Ridge, 4. Powell Basin, 5. Joinville Ridge, 6. Orkney Plateau, 7. Pirie Bank, 8. South Georgia Island, 9. Elephant Island, 10. Hesperides Trough.

[Orsi *et al.*, 1995], often associated with surface jets. The climatological position of the ACC's southern boundary coincides with the ASF's outflow at the WSC. In recent years, remotely sensed diagnostics (altimetry, sea surface temperature, gravity) have offered a synoptic picture of the fronts [Sokolov and Rintoul, 2007; Volkov and Zlotnicki, 2012]. These efforts focus on global definitions of the ACC fronts. Venables *et al.* [2012] undertake a regional analysis in the Scotia Sea that leads to local front definitions that can differ significantly from the global ones.

[6] This study provides the first Lagrangian observations of a direct transport pathway between the northwestern Weddell Sea and SGI using surface drifters. Both drifter trajectories and remotely sensed surface chlorophyll values between 2003 and 2012 reveal that Scotia Sea ecosystem dynamics are sensitive to variability in ACC fronts in Drake Passage.

2. Data and Methods

[7] Forty surface drifters were deployed in January 2012 across the core of the ASF, near Joinville Ridge in the northwestern Weddell Sea as part of the Gliders, Excellent New Tools for Observing the Ocean (GENTOO) project (Figure 1). The drifters were Clearsat-15 Minidrogué drifters, consisting of a surface buoy, wire tether, and holey-sock drogue designed to track currents at 15 m

depth. Processing of the drifter data followed the methods originally described in Hansen and Poulain [1996] and Thompson *et al.* [2009]. The expected drogue slip relative to the water is less than 2 cm s^{-1} for winds up to 20 m s^{-1} [Niiler *et al.*, 1995]. The 2012 GENTOO release maximized the number of drifters entrained in the ASF and thus exported to the Scotia Sea. Of the 40 surface drifters, 20 were equipped with GPS tracking, enabling a location fix to within 25 m. The remaining 20 drifters were tracked using the Argo system with an accuracy of approximately 350 m. Drifter trajectories were filtered to remove the effects of tides and inertial oscillations.

[8] Three different ACC front diagnostics were employed in the analysis of the drifter trajectories. The climatological position of the fronts [Orsi *et al.*, 1995] are shown in Figure 1. Synoptic positions of the fronts are calculated locally by associating contours of sea surface height (SSH) with regions of high SSH gradient, as pioneered by Sokolov and Rintoul [2007]. Volkov and Zlotnicki [2012] use a combination of satellite altimetry and Gravity Recovery and Climate Experiment data to update the ACC fronts. Their definition of the fronts in the Scotia Sea are similar to Sokolov and Rintoul [2007]. Finally, Venables *et al.* [2012] use hydrographic data, Argo floats and altimetry to define local ACC fronts within the Scotia Sea. Their analysis defines a range of SSH values for each front. Dynamic height data contain an arbitrary constant of integration

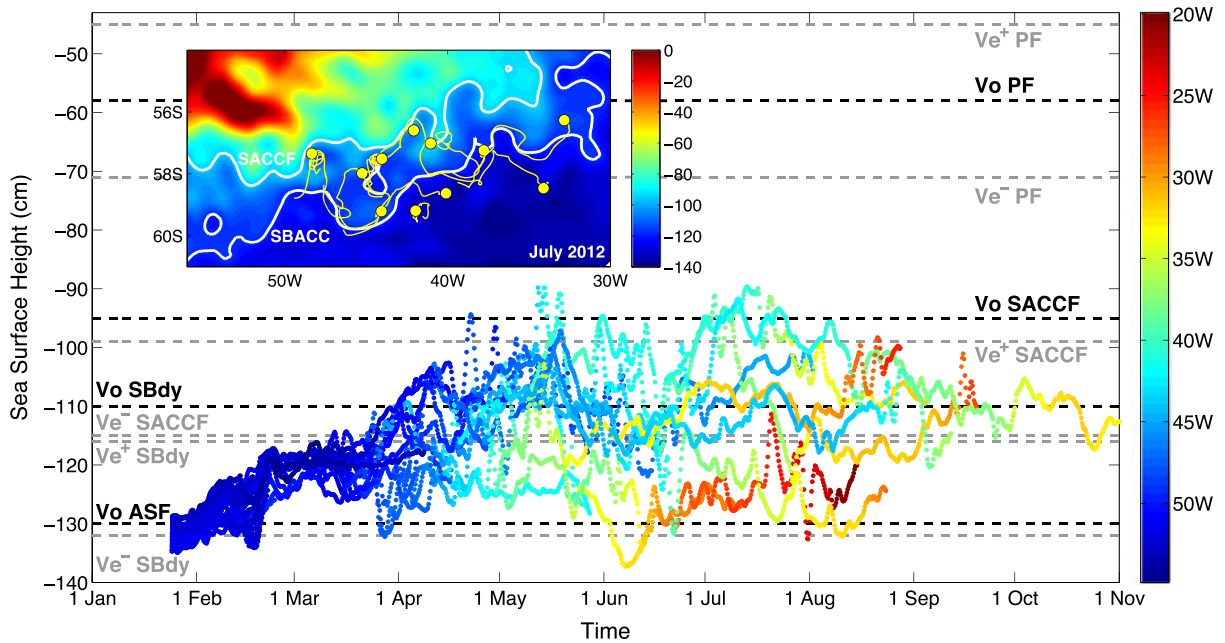


Figure 2. Time series of the drifter positions mapped into sea surface height space from maps of AVISO dynamic topography. Dashed lines indicate frontal positions and boundaries as determined by *Volkov and Zlotnicki* [Vo, 2012] and *Venables et al.* [Ve, 2012]. Color indicates the longitude of the drifter providing an estimate of downstream advection in the ACC. South Georgia Island is located at 37°W. (Inset) A snapshot of sea surface height along with the positions of the Polar Front and Southern ACC Front as defined by Vo. Circles show positions of drifters in the ACC with tails showing their path over the past 30 days.

but comparison of the *Volkov and Zlotnicki* [2012] and *Venables et al.* [2012] front positions is possible as both apply the absolute dynamic topography distributed by Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO).

[9] Ocean chlorophyll distributions are obtained from the MODIS satellite ocean color data (<http://oceanocolor.gsfc.nasa.gov>). Composite images are created from 8 day maps of 9 km level 3 chl-*a* images between November 2002 and October 2012. Indices for the Southern Annular Mode were taken from (www.antarctica.ac.uk/met/gjma/sam.html), developed by *Marshall* [2003].

3. Results

[10] Figure 1 shows the filtered trajectories of all 40 GEN-TOO drifters. The early stages of the trajectories are dictated by the frontal structure in the Weddell Sea. The separation of the drifter trajectories into two bands during its initial trajectory around the Powell Basin indicates that the ASF split into a front with two velocity maxima, which differs from the single front observed by *Thompson et al.* [2009]. The drifters remain shoreward of the Weddell Front that circles the Powell Basin. Critically, all drifter trajectories move cyclonically around Powell Basin before crossing the South Scotia Ridge. This is in contrast to the Antarctic Drifter Experiment, Links to Isobaths and Ecosystems (ADELIE) drifter deployment, where the ASF was observed to bifurcate over the South Scotia Ridge causing drifters to enter Bransfield Strait. This difference is a key reason for the higher percentage of drifters entering the Scotia Sea in 2012. Drifter trajectories are tightly constrained within the ASF around Hesperides Trough (Figure 1, inset) and ultimately

14 of the 40 drifters enter the Scotia Sea before the encroachment of sea ice. The red trajectories show the three ADELIE drifters that entered the Scotia Sea in 2007. The sites of exchange between the Weddell and Scotia Seas are limited to a series of gaps in the South Scotia Ridge (Figure 1c), consistent with the results of *Palmer et al.* [2012].

[11] Figure 1 shows the climatological positions of the ACC fronts (white curves) from *Orsi et al.* [1995]. The Southern ACC Front (SACCf) and the Southern Boundary of the ACC (SBACC) are tied to topography along the southern edge of Drake Passage [*Zhou et al.*, 2010]. Drifter trajectories freely exchange across the SBACC as this front coincides with the outflow sites from the Weddell Sea. Topography influences the surface flow downstream in the Scotia Sea as the drifter trajectories separate around Pirie Bank (Figure 1). Within the Scotia Sea there is significant movement of the drifter trajectories across the climatological position of the fronts, including a large meander that brings a pair of drifters near SGI's western continental shelf. All seven drifters that are advected at least as far east as 35°W are found south of SGI, consistent with the position of the SACCf. Downstream of SGI most drifter trajectories deflect northward along the eastern side of SGI.

[12] The ACC fronts undergo significant fluctuations, such that at any given time, the climatological positions may be poor indicators of the dynamical locations of the fronts. To consider the role of ACC frontal variability on the drifter trajectories, drifter positions were mapped into SSH space as a function of time. The dynamic topography, obtained from AVISO as weekly maps, were interpolated linearly in time and space to the drifter location so that a 6-hourly time series of SSH was compiled for each filtered drifter trajectory. The results of this analysis are shown in Figure 2. The drifters are

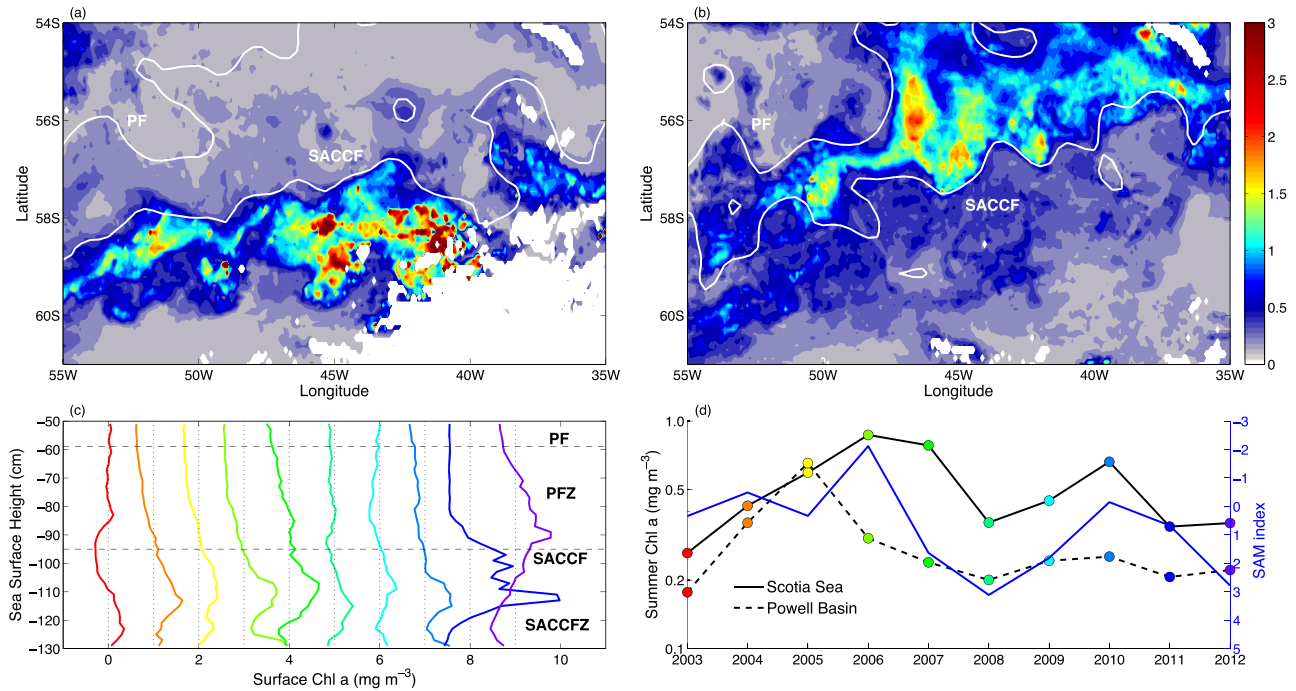


Figure 3. Monthly composites of surface chlorophyll for (a) November 2006 and (b) February 2012 in mg m^{-3} . The two curves indicate the instantaneous position of the Polar Front (PF) and Southern ACC Front (SACCF) on 15 November 2006 and 15 February 2012, as shown in Figures 3a and 3b, respectively. White regions indicate land or absence of data due to cloud cover. (c) Annual mean chlorophyll anomalies as a function of sea surface height for 2003 through 2012. The color of the curves corresponds to the years in panel (d). Anomalies are given as offsets from the dashed lines which are displaced for visual clarity. Dashed lines indicate positions of the SACCF and PF from *Volkov and Zlotnicki* [2012]; the frontal zones are found in between. (d) Time series of the austral summer mean chlorophyll in the Powell Basin (dashed line) and the SACC Frontal Zone (solid). The time series of the summer-mean Southern Annular Mode (SAM) index (blue line) is given for reference. Note the SAM index axis is reversed.

tightly constrained within the Weddell Sea due to focusing by the ASF but spread dramatically in late March and early April. While the drifter trajectories do not advance monotonically to the east, the color in Figure 2, which indicates longitude, provides an estimate of the downstream advection of the drifters in the ACC.

[13] Dashed lines in Figure 2 represent different estimates of the front positions from the studies of *Volkov and Zlotnicki* [2012] (indicated by Vo) and *Venables et al.* [2012] (indicated by Ve). The northern extent of the drifter trajectories are bounded by $\text{SSH} \approx -95$ cm; the drifters move freely across the SSH contour associated with the SBACC, -110 cm. The inset plot in Figure 2 emphasizes this result by showing portions of drifter trajectories from July 2012 along with the instantaneous positions of the SACCF and the SBACC in the middle of the same month. Note that two closed SSH contours appear in the SACCF frontal zone indicating the potential for eddy shedding to influence cross stream transport in this region. In addition to the drifter trajectories, the altimetry data shows that the SACCF is consistently associated with elevated SSH gradients [*Sokolov and Rintoul*, 2007], which is indicative of strong surface flows along the front (not shown).

[14] The identification of the SACCF as a dynamic barrier to transport is strengthened by an analysis of surface chlorophyll distributions in the Scotia Sea. Figures 3a and 3b show spatial maps of surface chl-*a* distributions in November 2006 and February 2012, respectively. Overlaid on these

panels are instantaneous positions of the PF and the SACCF on (a) 15 November 2006 and (b) 15 February 2012. The correlation between the ACC fronts and the lateral extent of the elevated chlorophyll regions is remarkable; these plots are representative of distributions in other years. The surface chl-*a* values located between 55°W and 40°W were also mapped into SSH space using the AVISO data. A zonally integrated time-SSH plot of surface chl-*a* reveals that throughout much of the year, chl-*a* is partitioned by the SACCF. This partitioning has a tendency to break down in January in certain years (2007, 2009, and 2010) when chl-*a* levels are high in both the SACC Frontal Zone (SACCFZ, south of the SACCF) and the Polar Frontal Zone (PFZ, between the PF and the SACCF). This partitioning appears in yearly (austral spring to fall) averages (Figure 3c). From 2003 to 2011, peak values of chl-*a* are bounded to the north by the SACCF; the SACCF also partitions chl-*a* in 2012 but peak values are found in the PFZ (Figure 3b).

[15] The peak in chl-*a* levels in the SACCFZ, in addition to numerical models that highlight the importance of sedimentary sources of iron for productivity [*Lancelot et al.*, 2009], suggests that variability in exported Weddell Sea water properties influences Scotia Sea ecosystem dynamics. Figure 3d compares the summer mean chl-*a* values within the SACCFZ between 55°W and 40°W with chl-*a* values found at depths less than 2500 m within the northwestern Weddell Sea. We focus on summer months to compare with the drifter data. Interannual variability of

chl-*a* in the two regions have a correlation coefficient of 0.49, which interestingly rises to 0.73 for a 1 year lagged correlation with Powell Basin leading the SACCFZ. This suggests that the Lagrangian pathways illustrated by the drifters also serve as pathways for iron injection. It is not clear why the PFZ shows elevated chl-*a* values in 2012, although an iron source upstream of the WSC may play a role [Frants *et al.*, 2012]. In particular, Kahru *et al.* [2007] and Park *et al.* [2010] have shown that eddy shedding near the Shackleton Fracture Zone can inject shelf waters directly into the PFZ.

4. Discussion and Conclusions

[16] The focused deployment of 40 surface drifters within the ASF along the eastern boundary of the Antarctic Peninsula provides the first Lagrangian observations of a direct transport pathway between the Weddell Sea and regions of persistently elevated chlorophyll levels in the Scotia Sea. The drifter trajectories confirm a pathway suggested in several previous studies [e.g., Murphy *et al.*, 2004; Thompson *et al.*, 2009; Renner *et al.*, 2012], as a potential mechanism for iron injection from the continental shelf that exerts an influence over Scotia Sea ecosystem dynamics. In 2012, the mean advection time for drifters to reach SGI (i.e., time to first reach 35°W) was 170 ± 49 days (Figure 1), but this value may change significantly with variability in the structure of the Weddell Gyre [Renner *et al.*, 2012]. From Figure 2, we conclude that the SACCF is likely to play the dominant role in regulating the interaction between Weddell Sea waters and those found around SGI. Our results also show that, at least in 2012, the Volkov definition of the SACCF was the most accurate of the three used here, with respect to being a barrier to cross-frontal surface transport.

[17] Meredith *et al.* [2008] identify a link between remote variability in Antarctic Bottom Water and the dynamic response of the Weddell Gyre to changes in surface wind forcing. Here, drifter trajectories and chl-*a* distributions indicate that changes to the structure and position of Weddell Gyre boundary currents also impact surface and intermediate water mass exchange across the WSC. In fact, the surface flow may present even more complicated dynamics due to the added interplay between the outflow of the ASF and the southern-most fronts of the ACC. Fluctuations in the position of the ACC fronts significantly influences the extent of Scotia Sea waters that are directly sourced by Weddell Sea waters.

[18] Renner *et al.* [2012], using a numerical model to advect virtual drifters, identified two distinct modes of surface circulation in the Weddell Sea, determined by the strength of the Southern Annular Mode (SAM). A weaker SAM was associated with more virtual drifters traversing the continental shelf, whereas during periods of stronger SAM, a stronger ASF located offshore of the shelf break entrained most drifters. Figure 3d shows that the summer SAM index is anti-correlated with interannual variations in the northern Weddell Sea and SACCFZ chl-*a* values. The correlation coefficients of the Powell Basin and SACCFZ regions with the SAM index are -0.40 and -0.51 , respectively. The details of this relationship are complicated by biological behavior and the intricacies of the iron cycle. Yet, this anticorrelation would be consistent with a reduction in the delivery of iron-rich shelf waters in strong SAM conditions caused by an

offshore shift of the ASF and/or a strengthening of the ASF that results in a more efficient cross-shelf transport barrier. Temporal variability in the ASF in response to wind forcing is the focus of ongoing work.

[19] This study highlights a need for an improved understanding of the dynamics that control the variability in exchange processes across the WSC. The ASF is extremely narrow as it exits the WSC and interacts with the ACC's southern boundary. It is likely that even weak meandering and eddy shedding will be sufficient to enable cross-shelf transport. The discussion here has focused here on potential routes for iron injection and the impact on Southern Ocean ecosystems, but the interaction of Weddell Sea and ACC frontal currents at the WSC, including their response to changes in surface wind and buoyancy forcing, is also likely to impact the ventilation and the uptake of CO₂.

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